MOBILE ROBOTS FOR OUTDOOR SECURITY APPLICATIONS

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ABSTRACT

A comprehensive robotic security solution for outdoor storage facilities is provided by the Mobile Detection Assessment and Response System-Exterior (MDARS-E). The system consists of multiple supervised autonomous platforms equipped with intruder detection, barrier assessment, and inventory assessment subsystems commanded from an integrated control station. The exterior platform is only one component of the overall MDARS system, which supports a variety of remote resources including interior platforms and fixed-place security sensor suites. All such resources are controlled by the Multiple Resource Host Architecture (MRHA), with minimal human (i.e., security personnel) supervision required.

In operation, the MRHA commands multiple exterior platforms to execute random patrols in the secured area, checking for intruders and interrogating barrier devices (i.e., door locks) and high-value assets equipped with radio frequency identification (RFID) transponder tags. The Intrusion Detection System (IDS) consists of the sensor hardware and associated processing necessary to detect intruders while the vehicle is performing random patrols. The sensor suite combines color CCD and forward-looking infrared (FLIR) imagers with a coherent pulsed Doppler radar enabling the IDS to detect motion, pattern characteristics, and range as well as radar and thermal signatures. The image streams are processed using pixel-level change-detection algorithms sensitive to scene motion. The radar returns are processed to provide range (time of flight) and Doppler (phase) information. Further onboard processing allows the system to track the behavior of the detections over time in order to classify the targets and reduce the nuisance alarm rate.

This paper provides an overview of the MDARS-Exterior security system, with a special focus on the recent end-of-contract demonstration at Aberdeen Proving Ground, Maryland.

1. Background

MDARS is a DoD development effort managed by the Product Manager, Physical Security Equipment (PM-PSE), with SPAWAR Systems Center, San Diego (SSC-SD) providing technical direction and MRHA development. The MDARS system, which provides an automated robotic security capability for storage yards, petroleum tank farms, rail yards, and arsenals, includes multiple supervised-autonomous platforms equipped with intrusion detection, barrier assessment, and inventory assessment subsystems commanded from an integrated control station.

The MDARS-Interior robot (Holland, et al., 1995; Laird, et al., 1999), designed and built by Cybermotion, Inc., of Roanoke, VA, for use in semi-structured indoor environments, is self-navigating.

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Once provided with a map of the assigned warehouse, it patrols up and down the aisles in a pseudo-random fashion reporting back any security problems encountered. It uses both Doppler radar and passive-infrared motion detection to sense possible intruders. For inventory tracking, the MDARS-Interior prototypes are currently outfitted with Savi Technology *Model CP-1010A-1* interrogators, which query special RF transponder tags affixed to high-value or sensitive items. Several of these indoor robots can patrol simultaneously, providing complete coverage of multiple warehouse interiors.

2. Exterior Robotic Vehicle

The MDARS-Exterior platform prototype (Figure 1) was developed by Robotic Systems Technology (RST), Westminster, MD, under a Broad Agency Announcement (BAA) contract (Myers, 1994). The four-wheel hydrostatic-drive vehicle is capable of automatic obstacle avoidance, accurate differential-GPS-based navigation, manual teleoperation, visual operator assessment, and two-way audio communication with a suspected intruder. Powered by a 25-horsepower Kubota diesel engine, the platform can operate on concrete, blacktop, and crushed stone roads for 12 continuous hours at a time.

Figure 1. The MDARS-Exterior vehicle during recent testing at Aberdeen Proving Ground, MD, in October 1998.

2.1 Navigational Subsystem

The navigational needs of the MDARS-Exterior robotic vehicle can be simplistically described as moving from point A to point B along a pre-defined trajectory without running into anything. Practical implementation of such is addressed through a Kalman-filter approach, combining inputs from differential GPS, a fiber-optic gyro, wheel odometry, and landmark recognition, as discussed below.

2.1.1 Differential GPS

A NovAtel *RT-2* differential GPS system serves as the primary navigation sensor, providing centimeter-level vehicle position updates in real-time. This 24-channel dual-frequency (L1/L2) receiver uses Narrow Correlator Technology to achieve a nominal position accuracy of 2 centimeters. It typically requires 70 seconds for the initial fix, and can support subsequent position update rates under 0.2 seconds.

A comprehensive DGPS survey (and follow-on evaluation of the NovAtel *RT-20*, Ashtech *Z-12*, and a Premier unit) was performed by RST (Grempler, et al., 1995) prior to the MDARS-Exterior Detailed Design Review. The *RT-2* was selected due to its excellent kinematic tracking, static and dynamic accuracy, compact VME board design (the complete system resides on a single 3U x 160-millimeter form-factor Eurocard), low power consumption, and envisioned potential for future cost reduction.

2.1.2 Gyroscope

A gyroscopic sensor can directly measure the rotational velocity of the object to which it is attached. In the past, such sensors were mechanical in nature, sensing the change in direction of some actively sustained angular or linear momentum, typically a spinning wheel mass or vibrating tuning fork. As a consequence, these devices were relatively heavy, consumed a lot of power, and lacked long-term reliability because of the moving parts. Several new technologies (fiber-optic, quartz-crystal, and piezoelectric-ceramic) have recently emerged, enabling manufacturers to produce solid-state, lightweight, inexpensive, and reliable rotational rate sensors (Everett, 1995).

Modern solid-state rate gyros incorporate electrostatic or piezoelectric (as opposed to electromagnetic) actuation schemes driving a variety of small and even micromachined vibratory elements (i.e., strings, bars, cylinders). Any rotation of the gyro causes induced Coriolis forces in an orthogonal plane, and the measured amplitude of the subsequent deflection of the vibrating element is proportional to the rate of turn. Fiberoptic gyros, on the other hand, sense angular displacement based on an optical principle known as the Sagnac effect, which detects rotation-induced changes in effective path length for two counter-rotating beams of light traveling in opposite directions around a fiber-optic coil (Everett, 1995).

Early trials were conducted with the solid-state Systron Donner *Gyrochip II*, which employs a micromachined quartz-crystal tuning fork element. The Andrews *RD2030* fiber-optic gyroscope was ultimately selected for use on the MDARS-E prototype platform due to its improved sensitivity at comparable cost.

2.1.3 Dead Reckoning

Wheel odometry sensors provide a low-cost and reliable (albeit somewhat inaccurate) method for calculating the relative distance traveled in a given direction by measuring tangential displacement as a function of tire rotation. The MDARS-E platform uses phase-quadrature wheel encoders to increase resolution and enable unambiguous quantification of forward and reverse motion. The integral encoder is designed around two hall-effect sensors and a magnetic ring with alternating north and south poles evenly distributed along its outer circumference. The hall-effect sensors are attached to a housing which

is installed over the magnetic ring in order to sense its rotational motion. A 60-pole magnet is employed to generate 240 ticks/revolution, which corresponds to a 0.3-inch distance-measurement resolution along the longitudinal axis of vehicle movement.

The encoder assembly is installed axially with respect to the hydraulic wheel motor so as to directly measure tire rotation. This type of configuration can survive under rugged outdoor conditions since its workings are completely sealed and protected underneath the wheel rim. Identical encoder assemblies are installed on each of the four hydraulic wheel motors, but only the rear-wheel encoders are currently used as measurement inputs into the navigation system because they experience less slip than the front wheels (in the case of an Ackerman-steered configuration).

2.1.4 Landmark Referencing

In areas where differential GPS coverage is poor, or where navigation accuracy needs to be extremely precise (i.e., driving through a narrow gate opening), a Landmark Referencing System is used to augment dead reckoning. Such a capability provides periodic high-confidence updates of absolute position and heading measurements to null out cumulative dead reckoning errors. (The heading and position information must be very accurate in order for the dead reckoning system to operate within allowable tolerances over any significant distance.) The key to robust landmark recognition, therefore, is to make the associated target attributes simple, inexpensive, easy to install, and completely unambiguous.

To accomplish this goal, the MDARS-Exterior Landmark Referencing System uses a special laser-based polarized proximity sensor (Banner Engineering model *Q45BB6LLP*) to positively identify the presence of a retroreflective landmark target. The landmarks typically are vertical poles covered with retroreflective material precisely situated at known surveyed positions. When the Banner proximity sensor detects an expected landmark, it triggers the obstacle avoidance laser to measure the range towards the landmark at its perceived azimuth. The vehicle's absolute position and heading can then be computed from this measured range and bearing to the known position of the reference landmark.

2.1.5 Navigation System Implementation

The navigation system utilizes redundant mechanisms (i.e., differential GPS, rate gyro, dead reckoning, and landmark referencing) to achieve a robust solution for handling real-world conditions. A Kalman filter approach has been applied to integrate the measurement data obtained from all the sensors and produce a best-estimate of the vehicle's current location. The filter accommodates multi-rate sensors, with the navigation system modeled as a random process and the sensors as noisy measurements. A block diagram of the approach is shown in Figure 2.

Extensive characterization of each of the navigation sensors was done in order to develop functions that accurately model their respective measurement errors under a wide range of circumstances. Several low-level algorithms were developed to increase the accuracy of the estimated velocity, heading, and rate-gyro measurements. The best measurement available for a given process is passed along to the Kalman filter, which calculates corresponding state outputs. The state outputs of the Kalman filter are then used

by path-following algorithms so the vehicle can be accurately controlled to achieve the desired trajectory.
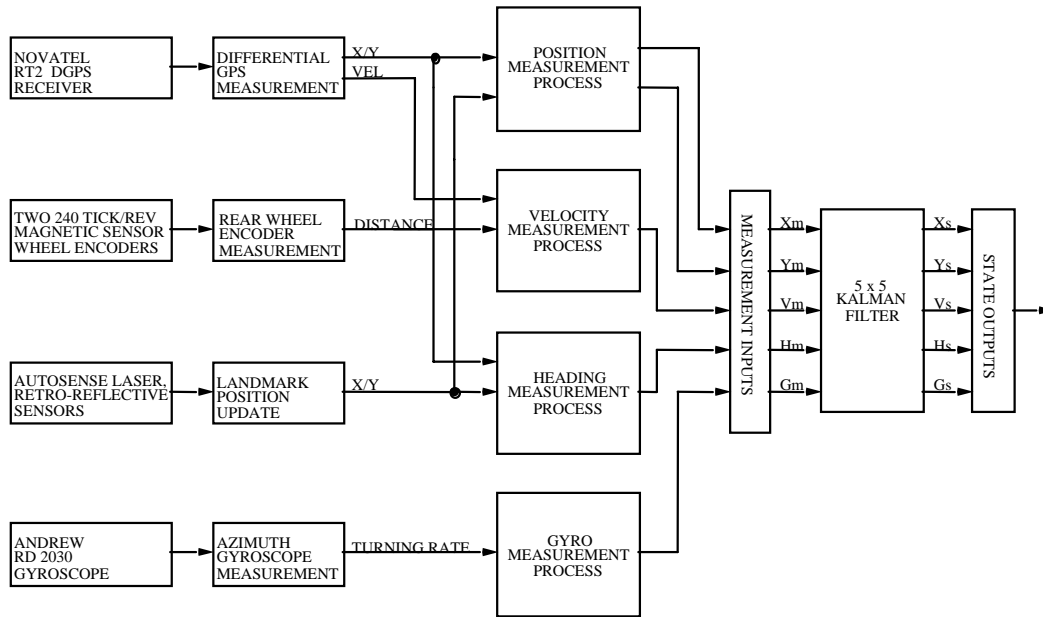

Figure 2. Block Diagram of MDARS-E Navigation System.

2.2 Obstacle Avoidance Subsystem

The MDARS-Exterior vehicle is required to operate over unimproved roads and fairly rough terrain at speeds up to 9 miles per hour, automatically avoiding obstacles greater than 6 inches and breaches wider than 8 inches. The collision avoidance strategy therefore incorporates a two-tier layered approach, wherein long-range (i.e., 0-100 feet) low-resolution sensors provide broad first-alert *obstacle-detection* coverage, and shorter-range (i.e., 0-30 feet typical) higher-resolution sensors are invoked for more precise *obstacle-avoidance* maneuvering. Systems currently installed include: 1) radar, 2) laser ranging, 3) ultrasonic ranging, and, 4) stereo vision.

2.2.1 Radar

The radar system is a bistatic X-band radar manufactured by General Microwave of Amityville, New York. The MDARS configuration employs five discrete beams fanning out horizontally in the front of the vehicle, and two additional beams arranged horizontally in the rear of the vehicle. The radar system has a 1- to 2-foot minimum range, 0.1-foot range resolution with 0.5-foot range accuracy, and is capable of detecting humans at 30 feet and larger targets (i.e., vehicles) as far away as 70 feet. Each front beam covers 15 degrees in both elevation and azimuth, for a total coverage of 15 degrees vertical by 75 degrees horizontal. The rear beams cover 15 degrees in elevation and 45 degrees in azimuth for a total coverage of 15 degrees vertical by 90 degrees horizontal.

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A frequency-stepped ranging technique is employed that monitors the phase changes for each of the frequency steps, with a ranging solution for a given beam accomplished in 10 to 50 milliseconds (depending on the number of targets detected). Typically, the front five beams will be scanned in less than 100 milliseconds if no targets are found, generating an individual target report for each beam. If targets are detected, the scanning will take slightly longer, but the vehicle will simultaneously slow down to ensure accurate obstacle detection, and to compute the proper circumnavigation maneuver.

2.2.2 Laser

The laser scanner selected for the MDARS-Exterior application is manufactured by Swartz Electro Optics of Orlando, Florida. This particular unit has four scanning lines separated by 5 degrees in elevation, with each scan line sweeping 90 degrees in azimuth. A range measurement is taken every 0.5 degrees in azimuth, and each of the four lines is scanned 20 times per second (for a total of 80 scans per second). The sensor has a maximum range of 64 feet with a range resolution of 0.25 feet, and operates at a 904-nanometer wavelength, which has good immunity to sunlight. The laser is fully temperature compensated from -40 degrees to 60 degrees Centigrade.

Since each beam yields but a single scanned line, the vertical coverage consists of just four discrete elevations in space. Generally, this works well because the laser paints a full 3-D picture over time as the vehicle moves through a scene, and is only subject to blind spots when the vehicle is stopped. The detection algorithm compares the range received for a given azimuth with a predetermined threshold which is set based on the height of the obstacles to be detected. Any reported range below this threshold is considered an obstacle.

Difficulty occurs in setting the threshold for the scans that are illuminating the ground, since the range to the ground surface may change quickly as a function of surface topography and vehicle attitude. To compensate for ground surface variations, a function was developed to dynamically adjust the threshold by calculating an estimate of the ground, thus enhancing the robustness of the sensor output.

2.2.3 Ultrasonic

The front of the vehicle is outfitted with five ultrasonic transducers, while the rear of the vehicle has four transducers, each with a 20-degree circular beam pattern. The ultrasonic time-of-flight sensors have a 20 foot range with 0.1 foot range resolution, on-board AGC circuitry, and temperature compensation to allow for more accurate ranging. Manufactured in-house by RST, each compact transducer module has it's own microprocessor with a two-wire Controller Area Network (CAN) interface. Many modules can thus be daisy chained on the same bus and placed anywhere on the vehicle.

The Obstacle Avoidance computer coordinates ranging and reception of all modules allowing for maximum system flexibility. The modules can be pinged in a round-robin fashion, or all modules can receive while any one module transmits at a given instant. The latter technique helps to detect targets that may not be perpendicular to the transmitted beam. The ultrasonic module will listen for up to 40 milliseconds, a limit imposed by the amount of on-chip memory. Each module processes its stored data to determine the range and strength of any valid detection and then reports back to the Obstacle Avoidance system computer.

2.2.4 Stereo Vision

MDARS-Exterior also incorporates a *VFE-200* vision system (Figure 3) developed by David Sarnoff Research Center (DSRC) capable of processing stereo video images for the purpose of obstacle avoidance. The *VFE-200* utilizes the stereo disparity between two images taken with adjacent cameras to form the basis of a triangulation ranging technique characterized by Laplacian pyramid processing, electronic vergence, controlled horopter, and image stabilization (Burt, et al., 1992). By referencing the disparity to different surfaces of the image, the system is able to extract much usable range information from the scene. Analysis is performed over a subset of the region created by the overlapping camera fields-of-view. Within this area of interest, a search for corresponding patterns between left and right images is performed over a selected range of disparities. This image region and disparity range correspond to a three-dimensional volume (the observation window) in the physical space in front of the vehicle.

Although an eventual migration to FLIR video is anticipated, the initial video sources are synchronized CCD cameras with a resolution of 640 x 480 pixels. The cameras are mounted at a height of 1 meter from the ground surface, tilted downward at an angle of 12 degrees, with an interocular separation of 3.5 inches (see again Figure 1). The field-of-view of each camera is 40 degrees horizontal by 30 degrees vertical.
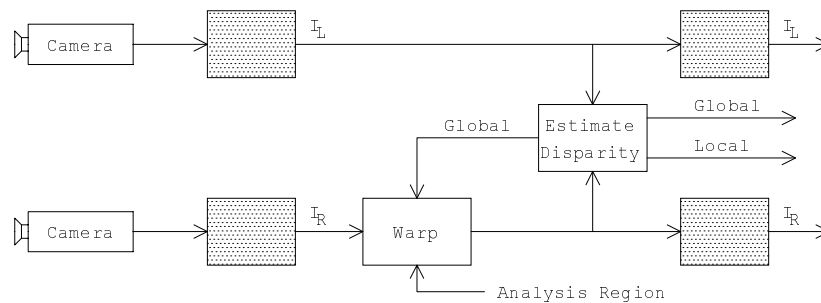

Figure 3. Block diagram of David Sarnoff stereo vision system (adapted from Burt, et al., 1992).

2.2.5 Obstacle Avoidance Sensor Fusion

A functional flow diagram of the Obstacle Avoidance System is shown in Figure 4. Data from each sensor is processed by a detection algorithm and weighted according to the performance of the sensor under a given set of operational conditions. The range and azimuth data of detected targets for each sensor are entered into a local obstacle map in the form of an X-Y certainty grid, where each grid element contains a value representing the confidence that an obstacle is situated at that location. The sensors overlap in coverage as much as possible, allowing the strengths of one sensor to compensate for the weakness of another.

Once detection information is entered for all available sensors, the obstacle map is analyzed to determine the closest obstacle in the forward direction of travel, in addition to where any nearby open areas might exist. This information is used to modify the velocity and steering commands, providing a reflexive functionality that allows the vehicle to circumnavigate obstacles and slow or even stop if necessary.

Polar histogram-based and iterative linear-based methods for reflexive operation and circumnavigation have been implemented.
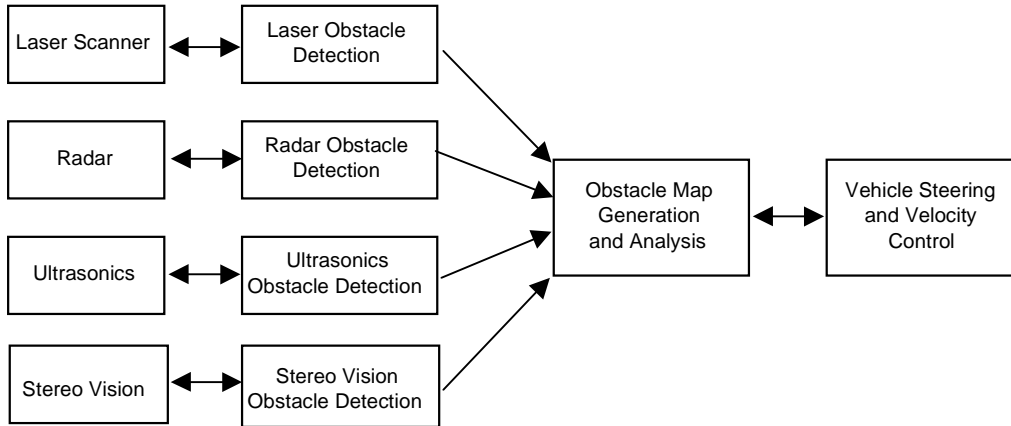

Figure 4. Functional Block Diagram of the MDARS-E Obstacle Avoidance System.

2.3 Security Sensor Subsystem

The MDARS-Exterior Intrusion Detection System (IDS) consists of a motion sensor suite which is selectively enabled while the vehicle is momentarily halted in execution of pre-defined but randomly executed patrols. The system must be able to detect a crawling, walking, or running intruder at a distance of 100 meters, even in darkness or the presence of smoke, fog, dust, and precipitation. The demanding nature of the required detection criteria necessitates the integration of complementary technologies which can sense motion, pattern characteristics, thermal signatures, and temporal behavior.
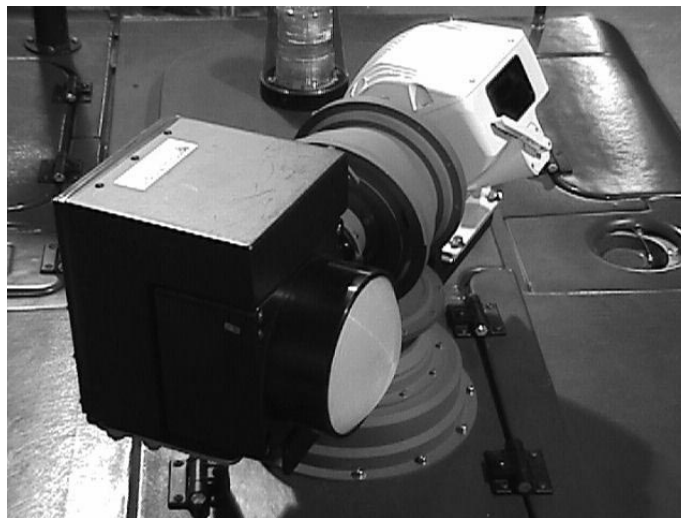

Figure 5. MDARS-Exterior pan-and-tilt unit, with the radar on the left and the FLIR on the right.

Accordingly, MDARS-E incorporates a two-layered sensor approach (i.e., vision and radar) to achieve a high probability of detection while simultaneously minimizing the number of nuisance alarms. The primary layer utilizes an infrared/vision-based (FLIR) system, which provides high angular resolution of

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a suspected intruder location within a scene. This information is used to slave a two-axis pan-and-tilt turret (Figure 5) on which both the radar and vision sensors are mounted to automatically track the designated target. The second layer, a long-range radar sensor, is thus optimally positioned to confirm the presence of any valid moving target, effectively minimizing nuisance alarms.

2.3.1 Vision-Based Intrusion Detection

The vision-based portion of the Intrusion Detection System consists of a low-cost Texas Instruments *NightCam* thermal imager mounted on a pan-and-tilt turret assembly, and the *VFE-200* vision processor (Section 2.2.4) developed by David Sarnoff Research Center. The uncooled thermal imager is a bump-bonded, capacitive-ceramic focal-plane array having a resolution of 328-horizontal by 245-vertical pixels, and a nominal field-of-view of 28 degrees horizontal by 14 degrees vertical. This imager is systematically scanned over a predefined field-of-regard in a step-and-stare fashion. Change-based moving target techniques are used to perform the initial detection.

The vision-based target detection algorithms can be considered as two processes (image stabilization and moving-target detection) that run independently. Images are captured at a 30-Hz rate and spatially aligned in order to reduce the effects of sensor motion and vehicle vibration. This is accomplished by fitting an affine transform between successive frames using a variable-sized window to indicate the region of interest. An affine transform is more effective than a pure translation in this case since the camera movement does not consist of pure rotation, and the lens distortion is significant.

Once the image is stabilized, two frames separated by a fixed amount of time (tuned to the type of motion anticipated) are used to provide change-based motion detection. The change detection is performed from low to high resolution using pyramid-based techniques, and the amount of separation between frames can be varied from cycle to cycle in order to allow sensitivity to a wide range of motion. A local gradient is then calculated at each pixel and used to normalize the detected motion with respect to the background motion. This step enables objects of interest to be detected even in the presence of motion blur caused by vehicle vibration. Detected pixel motion is then post-processed using connected-component analysis and blob detection, and the blobs are tracked in the image domain using a unique detection ID. These detections are then integrated further in the 3-D model and combined with detections from the pulsed-Doppler Radar.

2.3.2 Radar-Based Intrusion Detection

Referring to Figure 6, the high-level block diagram of the intruder detection radar consists of a 77-GHz pulsed-Doppler front-end developed by Millitech Corporation, Deerfield, MA, with the back-end interface, processing electronics, and digital signal processing (DSP) software developed by RST. The system is packaged as an integrated unit measuring 8.75 inches high by 6.75 inches wide by 9.75 inches long.
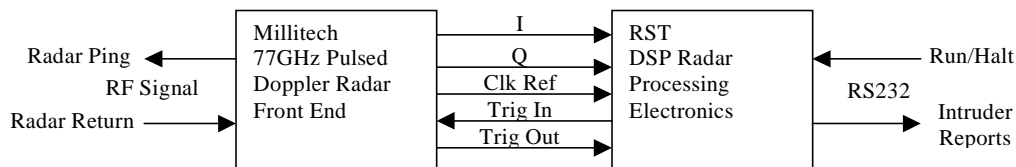
The DSP processing electronics are mounted in the rear of the enclosure to ensure the analog-to-digital conversion of the sensitive radar signals occurs very close to their source. System output is reduced to simple intruder reports conveying target range and velocity that are sent over an RS-232 interface to the main computer system onboard the MDARS-E platform.

The radar processing electronics are based around an Analog Devices *ADSP21060 SHARC* processor, high-speed analog-to-digital converters to sample the radar signals, and a complex programmable logic device (CPLD) that controls the timing of the data acquisition system. The *ADSP21060 SHARC* processor was chosen because it was specifically designed to efficiently compute Fast Fourier Transforms (FFTs), which typically form the basis of conventional radar signal processing.

Pulsed-Doppler radar operates by transmitting an RF pulse (ping) and sampling the received (reflected) signal at specified intervals. Each interval sampled for a single ping thus represents a range bin corresponding to a specific target distance. The prototype MDARS system samples at a 40-MHz rate, which equates to 12.5 feet between range bins. Each returning Doppler pulse is sampled 30 times in order to achieve a maximum detectable range of 375 feet (i.e., 30 range bins at 12.5 feet per bin). The Doppler pulse was sized to spread over multiple range bins to ensure that a moving target anywhere within the radar FOV would be detected when sampling at 40 MHz. A 35-nanosecond pulse is used, which spreads across two to three range bins, depending on target location (Cory, et al., 1998).

2.3.3 Intrusion Detection Sensor Fusion

Intruder validation is accomplished by using sensory information supplied by both the vision and radar systems. The vision system provides the geometric shape of the target and its angular location relative to the vehicle, while the radar system measures the distance to the target and its relative velocity radial to the vehicle. The target's perceived geometric shape and distance are then used to calculate its cross section for purposes of human target classification. This complementary mix of sensor technology allows for greater than a 99-percent probability of detection with less than a 1-percent nuisance alarm rate (Cory, et al., 1998).

Once a target is detected, it is tracked in the center of the collective field-of-view in order to provide verification using successive vision and radar-based detections. A track file is maintained on each detected target to correlate size, distance, speed, and other parameters over an extended period of time. This time-based integration approach allows the system to significantly reject nuisance alarms while using extremely high gains during the detection processes.

2.4 Barrier and Inventory Assessment Subsystem

For inventory tracking purposes, the exterior platform carries a Micron Corporation *MicroStamp 4100-20* interrogator for querying special RF transponder tags attached to high-value, controlled, or special-interest items throughout the storage facility. Two directional bistatic antennae are mounted on each side of the vehicle for communications with the RFID tags at pre-scheduled stops along its route (Figure 7). The tag used in conjunction with the MDARS-Exterior BAA prototype is the Micron *MicroStamp*, measuring 2.2 inches by 1.3 inches by 0.3, with an advertised battery life of 2 to 3 years. This particular

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tag has a somewhat limited maximum-read-range of 18 to 20 feet unobstructed line-of-sight, as compared to the desired effective read-range of 50-75 feet for this particular application.

Figure 7 A. Micron antennae (two small white squares above the PM-PSE logo); **B.** *MicroStamp* tag.

Information collected from the RFID tags is stored in a relational database. A user-friendly interface allows depot personnel to access the data to get regular or *ad hoc* reports on items which are being tracked. Typical output is in the form of exception reports highlighting potential problems, such as products missing from the facility or moved from their expected locations. Personnel can also use the system to look up the perceived location of a found item, not just the location where it is expected to be. This inventory tracking information is available in both text and map form.

The MDARS-Exterior robot also performs automated barrier assessment, which consists of remotely reading the status of high-security locking devices on containers or entry doors. The heavy-duty locks on these structures are each instrumented with a balanced magnetic switch interfaced to a modified *MicroStamp* tag, which senses whether the lock is open or closed and modifies its response accordingly. During patrol, the robotic vehicle reads the serial number and status of each lock from the tag, and transmits this information to the MDARS central control system. If a lock is found to be open, an alarm is raised so that a security patrol can investigate.

3. Command and Control

The MRHA is a distributed processing system that controls and coordinates the operation of multiple autonomous interior and exterior remote platforms. The system is designed to run automatically with minimal user oversight until an exceptional condition is encountered. This requirement implies the MRHA must be able to respond to exceptional events from several robots simultaneously. Distributed processing allows the problem to be split among multiple resources and facilitates later expansion through connection of additional processors. The individual processors are connected via an Ethernet LAN (Figure 8) that supports a peer-to-peer communications protocol. This distribution of function enables human supervision and interaction at several levels, while the hierarchical design facilitates delegation and assignment of limited human resources to prioritized needs as they arise (Everett, et. al., 1994).
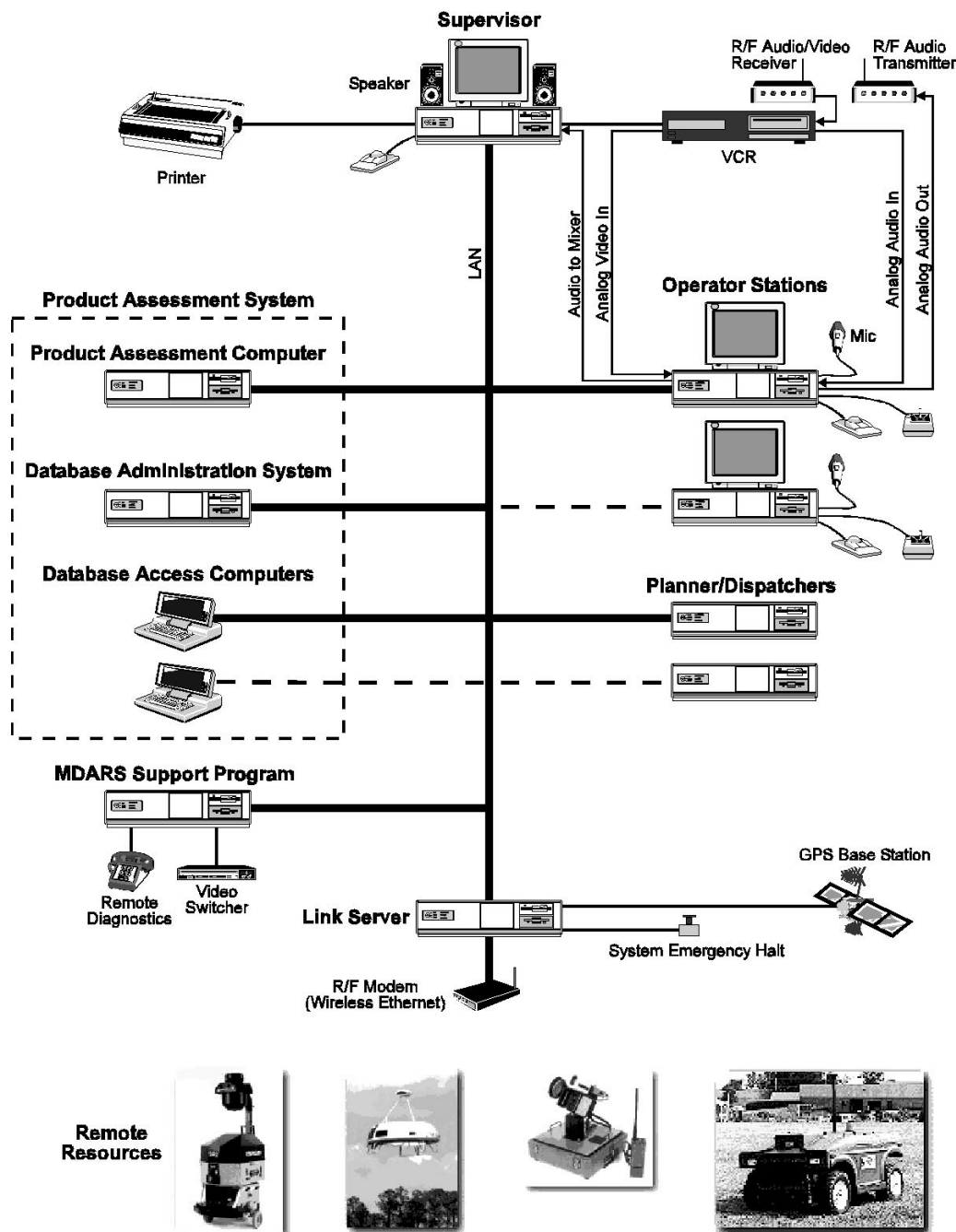
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Figure 8. Block diagram of the Multiple Resource Host Architecture.

The *Supervisor* process sits at the top of the hierarchy and is responsible for overall system management and coordination. The user interface provides a "big picture" representation of secured areas and system resources. The *Supervisor* has at its disposal a number of process resources, such as one or more *Operator Stations*, two or more *Planner/Dispatchers*, a *Product Assessment Computer*, and a *Link Server* (Laird, et. al., 1993).

User intervention is required only when a platform encounters an exceptional condition such as an environmental hazard or a security breach. Exceptional conditions are prioritized and an *Operator*

Station display is automatically invoked. The user is informed of the situation and of response options via the *Operator Station* display. This interface allows a user to directly influence the actions of an individual platform, with hands-on control of destination, mode of operation, and camera functions. Also, the display provides detailed operational and diagnostic system information. The *Supervisor* and *Operator Station* displays have been similarly configured to provide the user with consistent user-friendly, graphical interfaces. Both modules support point-and-choose menu buttons for user-selectable options, commands, and navigational waypoints.

The *Planner/Dispatcher* process (an integration of the Cybermotion "Dispatcher" and the SSC-SD "Planner") is responsible for assembling and downloading paths to platforms. The *Link Server* provides an interface to a data link between the host and the various robotic or fixed sensor platforms, and maintains a blackboard data structure of platform status information for immediate retrieval by other MRHA resources on the LAN.

The *Product Database Computer* maintains a listing of high-value inventory as verified by an RF tag reading system onboard the robot, correlated to geographical location within the warehouse. The *Product Assessment Computer* is responsible for uploading RF tag data from each platform, and for transferring the raw data to the *Product Database Computer*. *Database Access Computers* provide several database reports, and in the future can effect an automated interface between the MDARS Product Assessment System and existing site database systems.

4. Preliminary Test Results

An MDARS-E demonstration was conducted under the direction of Aberdeen Test Center (ATC) personnel at their 13-acre Unmanned Ground Vehicles Test Course on 14 and 15 October 1998. This demonstration involved the two prototype vehicles delivered to the government by RST at the conclusion of the Broad Agency Announcement (BAA) contract.

The demonstration consisted of a series of six daytime and two nighttime scenarios designed to show specific functions of the vehicles and supporting systems (i.e., communications, navigation, obstacle avoidance, intrusion detection/assessment, barrier assessment, and product assessment) under MRHA command and control (VanSeeter, 1998). Each demo scenario was conducted twice during the two-day period, with the two vehicles operating on both dirt and gravel roads, a grass field, and a 30-degree-slope calibrated hill. Two military HMWWVs, several CONEX containers, and a high-security lock installed on a CONEX container door were tagged with MICRON *MicroStamp* RF transponder tags as discussed in Section 2.4.

The ability to autonomously navigate in an unstructured environment was consistently demonstrated without incident over various road and field surfaces at speeds up to 21 kilometers per hour. Each vehicle easily maneuvered over the 15-centimeter log placed in its path, crossed the 20-centimeter breach, and had no problem negotiating a 30-degree hill (well in excess of the requirement to transit a 15-degree incline). The MRHA successfully orchestrated random patrols, pre-planned "canned" patrols, and "directed sends" (autonomous transit to user-specified locations) with two vehicles operating together in a shared patrol area. Communications were reliable out to 200 meters from the control

station with no repeaters. (The maximum testable distance was limited by geographic course constraints.)

The Obstacle Avoidance Subsystem successfully demonstrated the required ability to automatically halt when the path is completely blocked and request assistance from the MRHA. The ability to circumnavigate an obstacle partially blocking a path, however, was successfully performed only once during the demonstration period. In the other three attempts, the vehicle either did not complete the circumnavigation process or scraped the obstacle. In those trials, the system recognized the obstacle, began actions to avoid it, but failed to successfully complete the maneuver.

The system successfully interrogated barrier lock mechanisms at 4 meters line-of-sight and reported the lock status information to the MRHA. The assessment of tagged inventory items was demonstrated at 4 and 6 meters line-of-sight, but was not 100-percent successful every interrogation (i.e., not every tag was read during each interrogation), due to the limited effective-read-range of the *MicroStamp* tag. It should be noted, however, that the newly introduced Micron *4100-20* interrogator was received for integration only two weeks prior to the demo. (The previous model *4021* tested by SSC-SD proved too slow for the expected tag density of the MDARS application).

The detection of a human in motion was demonstrated, but not consistently at the 100-meter range requirement. While the speed at which the "intruder" approached the vehicle was not established or controlled, the general direction of approach was preplanned but not strictly enforced. The intruder walked upright, directly towards the vehicle, until detection was verified. For purposes of this demonstration, the distance of the intruder from the vehicle was recorded for both warnings (vision-system detection only) and alarms (radar confirmation). During daytime scenarios, warning ranges were recorded at 90 and 91 meters and alarms at 77.5 and 73 meters, while at night, warning ranges were at 105 and 111 meters and alarms at 85 and 79 meters.

Additional extensive optimization and testing of both hardware and software is planned in preparation for formal Technical Feasibility Testing in January 2000.

5. Conclusion

Preliminary tests conducted by RST, SSC-SD, and ATC of the MDARS-Exterior BAA prototype vehicles have been quite promising to date. At no time during the weeks of demo preparation and execution in October 1998 did the system ever get lost, due in part, no doubt, to the minimal overhead occlusion which afforded an optimal view of the GPS satellite constellation. Additional efforts during the coming months will further test and optimize the Landmark Navigation Subsystem to provide further robustness under more adverse conditions typical of the real world. The Obstacle Avoidance System likewise performed well, given the caveat that full integration of the contributing subsystems (i.e., laser, radar, ultrasonic, and stereo) did not take place until just prior to the demo due to funding limitations and schedule constraints.

The first-generation Intruder Detection System was able to detect, track, and validate human intruders out to almost 100 meters with a near-zero nuisance alarm rate. The radar system performed well in measuring the velocity and distance to targets and detecting target motion, both radial and tangential to

the radar antenna. Planned improvements include increased maximum range as well as enhanced target tracking by utilizing the range and velocity measurements from the radar system to better predict the direction of target travel.

The ultimate cost savings associated with a production MDARS installation will vary considerably for each application based on a number of factors. The size and characteristics of the area to be secured directly influence the cost of the initial system set up. The exterior robotic platforms have a target cost of $150K, while the full-up operator's console runs about $25K to $65K, depending on a variety of options. Associated support equipment such as RFID tags and locking devices must be considered, as well as the costs of linking the robots to the console via hardwire, fiber-optic, or RF relays.

These estimated installation costs must be weighed against the value of the items stored, expected loss rates, and the costs associated with securing and managing these items by conventional means. It is expected that MDARS robots will save money by reducing loss, allowing a re-engineering of certain inventory management and security functions, and in certain cases reducing the number of personnel required to perform these functions. The Department of Defense feels the potential benefits of MDARS far outweigh the risks and is thus moving ahead to place these systems at selected sites, initially within the continental United States, but ultimately world-wide.

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